CMOS ACTIVE PIXEL SENSORS: DESIGN FOR SCIENTIFIC APPLICATIONS

Renato TURCHETTA[#], Andrew CLARK, Jamie CROOKS, Andrea FANT, Marcus J. FRENCH, Przemyslaw GASIOREK, Nicola C. GUERRINI, Lawrence L. JONES, Quentin MORRISSEY, Mark PRYDDERCH, Filippos ZAKOPOULOS, Nick R. WALTHAM

Rutherford Appleton Laboratory, Chilton, Didcot, Oxfordshire, OX11 0QX;United Kingdom

ABSTRACT : *Scientific applications demand high performance CMOS Active Pixel Sensors. This paper will discuss where critical improvements are needed and describe how to achieve them. Our current drive in image sensor developments stem from the general needs of low-noise, high dynamic range, data sparsification (either on-chip or on-pixel), high rates, radiation hardness, sensor thickness and sensitive area.*

1 - INTRODUCTION

Silicon devices have been used since the 60s for the detection of radiation [1]. The interest of MOS devices was immediately recognised and arrays were designed. However, since their invention in 1970 [2], Charge Coupled Devices (CCD) became the main imaging devices.

In the early '90s [3, 4, 5], CMOS Active Pixel Sensors were proposed. It was immediately recognised that CMOS APS, or Monolithic Active Pixel Sensors, MAPS, have several advantages.

- MAPS are made in standard CMOS technology.
- Being monolithic, MAPS avoid the problems related to bump-bonding or other types of connections.
- Because of the shrinking size of transistors, pixels can be made very small or more functionality can be integrated in the same pixels [6, 7, 8].
- MAPS have very low power consumption [9].
- Deep submicron CMOS is radiation resistant [10].
- Several functionalities can be integrated on the same chip together with the sensor arrays. This brings simplification at the system level and hence reduction of costs.Pixels can be accessed randomly, trading off resolution or array size with readout speed or

[#] Corresponding author : r.turchetta@rl.ac.uk

Report Documentation Page

Form Approved
OMB No. 0704-0188

1. REPORT DATE	2. REPORT TYPE	3. DATES COVERED
13 JUL 2005	**N/A**	**-**

4. TITLE AND SUBTITLE	5a. CONTRACT NUMBER
CMOS Active Pixel Sensors: Design For Scientific Applications	5b. GRANT NUMBER
	5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)	5d. PROJECT NUMBER
	5e. TASK NUMBER
	5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **Rutherford Appleton Laboratory, Chilton, Didcot, Oxfordshire, OX11 0QX;United Kingdom**	8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)	10. SPONSOR/MONITOR'S ACRONYM(S)
	11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release, distribution unlimited

13. SUPPLEMENTARY NOTES
See also ADM001791, Potentially Disruptive Technologies and Their Impact in Space Programs Held in Marseille, France on 4-6 July 2005., The original document contains color images.

14. ABSTRACT

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT	b. ABSTRACT	c. THIS PAGE			
unclassified	**unclassified**	**unclassified**	**UU**	**10**	

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std Z39-18

making it possible to track objects at very high speed [11].

- The readout and analogue-to-digital conversion can be massively parallel, being normally column-parallel, but in some cases it is even pixel-parallel [6, 7, 8].
- They can be made very easy to use, limiting the readout system requirements to digital I/Os.

2 - RADIATION DETECTION WITH CMOS SENSORS.

CMOS sensors were originally proposed for the detection of visible light and they are used this way in consumer products. However, CMOS sensors can also be used for the detection of electromagnetic radiation and charged particles, as explained in [12]. The detection of minimum ionising particles with 100% efficiency was proposed in [13] and then first demonstrated [13, 14, 15, 16]. Use of a CMOS MAPS with electrons was demonstrated for energies going from around 100 keV [17, 18] down to about 20 keV [28]. Different ways of achieving UV detection efficiency are shown in [19, 29]. Efficient detection of X- or γ- rays can also be achieved with the use of a converter or scintillator, given that the typical thickness of the sensitive layers is less than 20 μm.

3 - NOISE AND DYNAMIC RANGE

In CMOS MAPS the main source of noise is the reset noise (see for example [13] and references there). Reset noise is well known and can normally be eliminated by Correlated Double Sampling (CDS). However, it is not easy to apply this technique in MAPS, since it relies on storage of the reset level either inside the pixel or outside the pixel. In the latter case, real-time CDS requires a memory, either digital or analogue, of the same size of the pixel array. For large formats, e.g. megapixel sensors, this can be highly impractical. Off-line CDS [15] is technically easier to apply, but can only be used in specific applications where speed and memory requirements are not too tight. In the case of storage in the pixel, a modification to the standard structure of a diode and three transistors is required. As a sensor, either a photogate [1] or a pinned-diode [21] can be used. Another alternative is to integrate capacitances in the pixels to store the reset level [22]. The in-pixel CDS comes with some disadvantages since the thermal noise is increased by $\sqrt{2}$ and the speed is normally halved by the need of reading out both the reset and the signal sample sequentially. However, very good performances in terms of noise have been presented, and probably the best result is 2 e^- rms noise [21]. However, in some cases, it is not possible to use the CDS and techniques for reducing the reset noise become interesting.

3.1 - HARD AND SOFT RESET

Some alternative structures for the reduction of noise have been presented [22, 23, 24]. In these techniques additional transistors need to be added in the pixel, reducing the fill factor and adding complexity into the design.

However, [26] shows that it is possible to have lower kTC noise even in the case of the simple 3-MOS pixel (fig. 1). If the gate-to-drain voltage V_{GD} on the reset transistor exceeds the transistor threshold voltage V_T, the reset switch is in strong inversion resulting in a "hard reset". If $V_{GD}<V_T$ the reset transistor enters the weak inversion region during the last phase of the reset, and a "soft reset" is performed. In a normal, hard reset, the full reset noise is left on the diode, i.e.

$$\mathrm{ENC}_{\mathrm{hard}} = \frac{1}{q}\sqrt{kTC} \qquad \textbf{[3.1]}$$

where q is the charge of the electron, k the Boltzmann's constant, T the absolute temperature and C the total capacitance seen at the reset node after the reset. This includes the diode capacitance as well as the gate capacitance of the input transistors as well as any other stray capacitance due to the reset transistors or the interconnect lines. Translated in electrons, this formula states that the reset noise is about 40 e^- rms for a capacitance of 10 fF. Since it is difficult to achieve input capacitances smaller than 5 - 10 fF, this formua indicates that the minimum reset noise achievable in hard reset is of the order of 20 –30 e^- rms

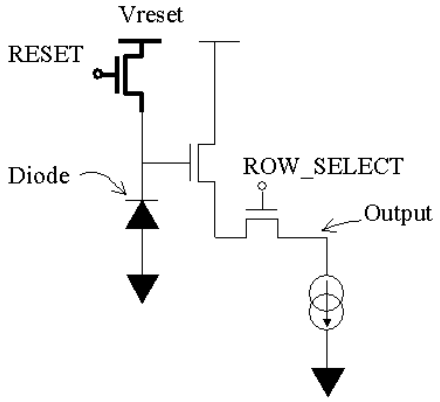

Figure 1 - Schematic of a 3 MOS transistor.

In the soft reset, the noise model is different and the noise variance is reduced by a factor $\sqrt{2}$ with respect to the hard reset:

$$\mathrm{ENC}_{\mathrm{soft,max}} = \frac{1}{q}\sqrt{\frac{kTC}{2}} \qquad \textbf{[3.2]}$$

However it is important to notice that this is the maximum level of noise produced by the soft reset. The actual ENC will depend on the amount of

charge left on the input node before reset as shown in [26] :

$$ENC_{soft}^2 = \frac{mKTC}{q^2}\left(1+\left(\frac{q^2\sigma_0^2}{mkTC}-1\right)*e^{-q^2*Q/mkTC}\right) \qquad \textbf{[3.3]}$$

where m is the weak inversion non-ideality factor and Q is the charge left by the previous reset. The function is an S-shaped curve whose upper limit is given by [3.2].

These results suggest that, in applications where very little charge is present in the input, or, stated differently, where the sensor is basically in the dark, the reduction of the reset noise can be higher than $\sqrt{2}$ and the reset noise can be reduced to about 10 e^- rms. We confirmed this experimentally by measuring the noise distribution of the pixels in an array of 64x64 pixels [28].

3.2 - FULL WELL CAPACITANCE AND DYNAMIC RANGE

In a MAPS, the charge-to-voltage conversion factor G at the input is fully determined by the capacitance C at the input node. The following relation holds

$$G[\mu V/e^-] = 160/C[fF]$$

The maximum voltage swing ΔV at the input is determined by the maximum voltage available in a given technology. This sets the full well capacity Q_{FW}, which turns to be proportional to C since

$$Q_{FW}[e-] = \Delta V[\mu V]/G[\mu V/e^-] \qquad \text{or}$$

$$Q_{FW}[e-] = \Delta V[\mu V]*C[fF]/160 \qquad \textbf{[4]}$$

If, following the conventions used in imaging detectors [30], we define the dynamic range as the maximum signal, i.e. the full well capacity, divided by the minimum noise, we find

$$DR = q\frac{\Delta V}{160}*\sqrt{\frac{pC}{kT}} \qquad \textbf{[5]}$$

where *p* is the reset noise reduction factor, equal to 2 in the case of soft reset for large signals or higher for lower signals. This shows that (see fig. 2) the dynamic range is proportional to the input capacitance C. For a given reset scheme, if small signals need to be detected, but dynamic range is not a priority, for example in vertex detectors in particle physics, C should be as small as possible. If the dynamic range is a priority, then C should be as high as possible, within the limits set by the detectability of the smallest signal.

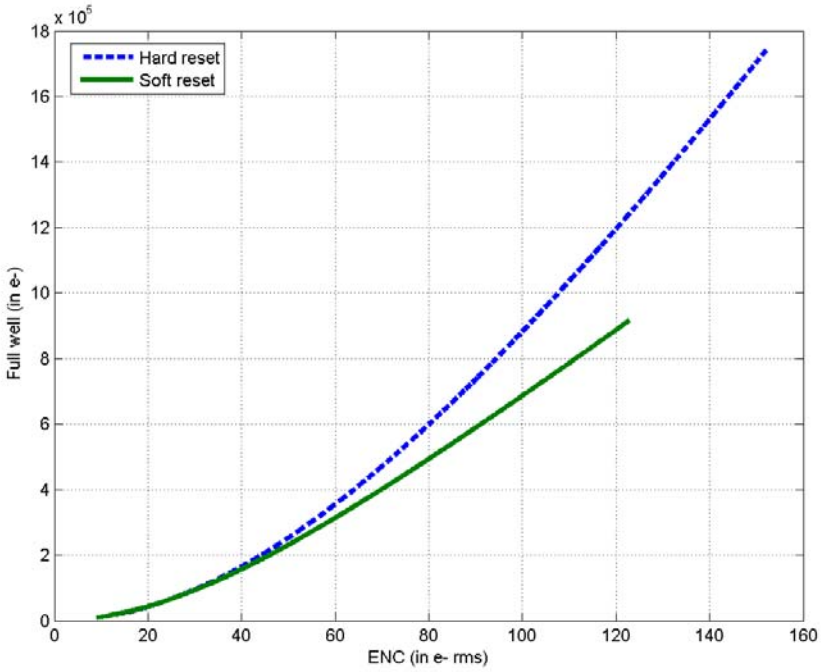

Figure 2 - Full well capacitance as a function of reset noise in hard and soft reset.

4 - READOUT RATE

Depending on the applications, the required readout rate and resolution can vary significantly. On one side of the spectrum, there are applications [19, 29] where high resolution (14 – 16 bits) and low readout rate (less than one frame per second fps) are demanded, and on the other one there are aplications where low resolution (8 bits maximum) and high readout rate (in excess of 10^4 fps) are requested [31]. The type of application will affect the type of readout scheme and in particular the type of analogue-to-digital conversion scheme to be used. To be able to respond to this wide range of requests from scientific users, we are developping a number of analogue-to-digital (ADC) solutions, ranging from in-pixel conversion to single-chip solutions, through column-parallel solutions. For each solution, a different architecture of the ADC has to be chosen.

The table 1 below summarizes the different type of architectures we have developed so far.

The single-ramp ADC is a very compact solution and can be integrated in a column [20] or even in a pixel. Its speed scales with $2^{N_{bit}}$ and it can than become rapidly impracticable for high resolution applications. The pipeline ADC is our favourite solution for high resolution [32] applications. It is however quite power hungry and occupies a large area, making it impossible to integrate a large number of them on a single chip. This is possible with successive approximation ADC. It is relatively easy to achieve a moderate number of bits (10 – 12), and the architecture is

inherently low power and compact. Their speed scales linearly with the number of bits N_{bit}. They are a favourite choice for column-parallel applications where moderate resolution and relatively high speed is required.

	Geometry	**Speed**	**Resolution**	**Power consumption**
Single ramp	Column	Low	High	Medium
Single ramp	Pixel	High	Low	High
Pipeline	Area	High	High	High
Succesive approximation	Column	Medium-high	Medium-High	Low

Table 1

The two figures below summarize these considerations in the case of 8 and 16-bit resolution respectively. At low resolution, the pixel parallel solution is the favourite one for frame rate. However, the pixel parallel solution requires a complicated structure in the pixel and this reduces the fill factor. As shown in figure 4, at high resolution the pixel parallel solution is better than a more conventional successive approximation ADC only for very high pixel counts, since the frame rate is uniquely determined by the long time needed to make a conversion. This is without taking into account any loss of image quality due to the reduced fill factor.

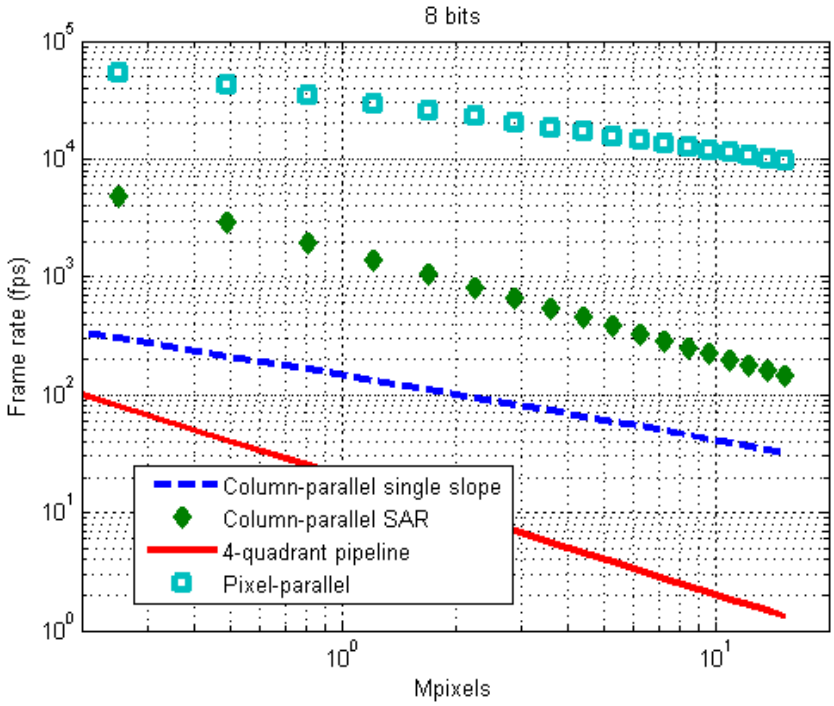

Figure 3 - Frame rate as a function of number of millions of pixels for a square sensor and for different ADC architectures. 8-bit resolution.

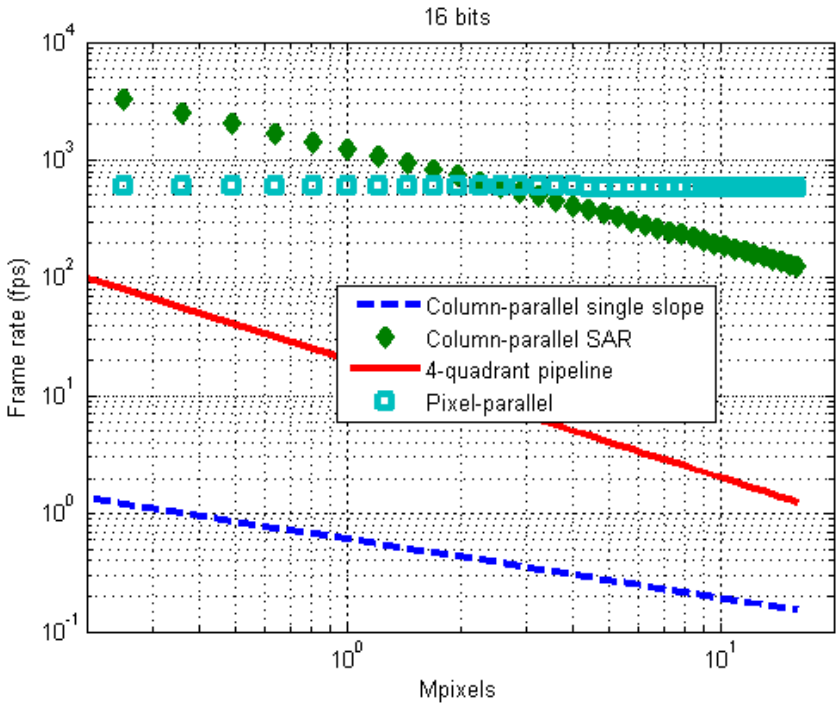

Figure 4 - Frame rate as a function of number of millions of pixels for a square sensor and for different ADC architectures. 16-bit resolution.

5 - CONCLUSIONS

CMOS sensors found their first applications in the detection of visible light and became widely spread in consumer applications. We are now developing this technology to meet the stringent requirements of scientific applications. CMOS sensors can be efficiently used to detect a broad spectrum of electromagnetic radiation and charged particles.

The dominant source of noise, the reset noise, can be reduced and, at low illumination levels, noise in the range of 10 e^- rms can be obtained, without any correlated double sampling. Different types of analogue to digital converter architectures allow to trade off between speed and resolution required. We anticipate that the use of CMOS sensors for scientific applications will expand in the next few years.

6 - REFERENCES

[1] E. R. Fossum, *CMOS Image Sensors: Electronic Camera-On-A-Chip*, IEEE Trans. on Electron Devices, vol. 44, no.10, Oct. 1997, 1689-1698

[2] W. S. Boyle and G. E. Smith, *Charge Coupled semiconductor devices*, Bell System Tech. Journal, vol. 49, 1970, 587-593

[3] E. R. Fossum, R. K. Bartman and A. Eisenman, *Application of the active pixel sensor concept to the guidance and navigation*, Proceeding of SPIE, vol. 1949, 1993, 256-265

[4] O. Yadid-Pecht, R. Ginosar and Y. Diamand, *A random access photodiode array for intelligent image capture*, in IEEE Trans. On Electron Devices, vo.l. 38, 1772-1780, Aug. 1991

[5] B. Dierickx, G. Meynants, D. Scheffer, *Near 100% fill factor CMOS active pixels*, Extended programme of the 1997 IEEE CCD & Advanced Image Sensors Workshop, Belgium

[6] D. X. D. Yang, A. El Gamal, B. Fowler and H. Tian, *A 640x512 CMOS Image Sensors with Ultrawide Dynamic Range Floating-Point Pixel-Level ADC*, IEEE Journal of Solid-State Circuits, vol. 34, n. 12, Dec. 1999, 1821-1834,

[7] D. X. D. Yang, B. Fowler and A. El Gamal, *A Nyquist-Rate Pixel-Level ADC for CMOS Image Sensor*, IEEE Journal of Solid-State Circuits, vol. 34, n. 3, March 1999, 348-356

[8] S. Kleinfelder, S. H. Lim, X. Liu and A. El Gamal, *A 10,000 frames/s CMOS Digital Pixel Sensor*, IEEE Journal of Solid-State Circuits, vol. 36, n. 12, Dec. 2001, 2049-2059

[9] K.-B. Cho, A. Krymski, E. Fossum, *A Micropower Self-Clocked Camera-on-a-chip*, Extended programme of the 2001 IEEE CCD & Advanced Image Sensors Workshop, Lake Tahoe, USA

[10] E.S. Eid et al., *Design and characterisation of ionising radiation-tolerant CMOS APS image sensors up to 30 Mrad(Si) total dose*, IEEE Trans. On Nucl. Science, Dec. 2001, vol. 48, n. 6, 1796-1806

[11] G. Yang, C. Sun, C. Wrigley, D. Stack, C. Kramer, B. Pain, *Dynamically Reconfigurable Imager for Real-Time Staring Vision Systems*, Extended programme of the 2001 IEEE CCD & Advanced Image Sensors Workshop, Lake Tahoe, USA

[12] R. Turchetta, *CMOS Monolithic Active Pixel Sensors (MAPS) for scientific applications*, Proc. of the 9th Workshop on electronics for LHC experiments, 28-33, Amsterdam, 2003

[13] R. Turchetta et al., *A monolithic active pixel sensor for charged particle tracking and imaging using standard VLSI CMOS technology*, Nucl. Instr. and Methods A 458 (2001) 677-689

[14] G. Deptuch et al., *Simulation and Measurements of Charge Collection in Monolithic Active Pixel Sensors*, Nuclear Instruments and Methods A 465 (2001) 92-100

[15] G. Claus et al., *Particle Tracking Using CMOS Monolithic Active Pixel Sensor*, , Nuclear Instruments and Methods A 465 (2001) 120-124

[16] G. Deptuch et al., *Design and Testing of Monolithic Active Pixel Sensors for Charged Particle Tracking*, IEEE Nucl. Science Symposium Conference Record, 2000, vol. 1, 41-48

[17] A. R. Faruqi et al., *Direct single electron detection with a CMOS detector for electron microscopy*, presented at IWORID 2004, submitted to Nucl. Instr. and Methods A

[18] P. P. Allport et al., *CMOS Active Pixel Sensors for Ionising Radiation*, presented at IWORID 2004, submitted to Nucl. Instr. and Methods A

[19] M. Prydderch et al., *A large area CMOS Monolithic Active Pixel Sensor for Extreme Ultraviolet Spectroscopy and Imaging*, proccedings of SPIE conference, Electronic Imaging, vol. 5301, 2004, 175-185

[20] M.L.Prydderch et al., *A 512x512 CMOS Monolithic Active Pixel Sensor with Integrated ADCs for Space Science*, Nucl. Instr. and Methods A 512 (2003) 358-367.

[21] A. Krymski, N. Khaliullin, H. Rhodes, *A 2e noise 1.3 Megapixel sensor*, Extended programme of the 2003 IEEE Workshop on CCD and Advanced Image Sensors

[22] R. Turchetta et al., *FAPS, a CMOS sensor with multiple storage for fast imaging scientific applications*, Extended programme of the 2003 IEEE Workshop on CCD and Advanced Image Sensors

[23] B. Fowler et al., *Low noise readout using active pixel sensor*, Proc. SPIE 3965, pp126-135, 2000

[24] R. B. Merrill, *kTC noise cancellation*, Extended programme of the 2001 IEEE Workshop on CCD and Advanced Image Sensors, June 2001, Lake Tahoe, USA

[25] S. Kleinfelder et al., *Novel integrated CMOS pixel structure for Vertex detectors*, IEEE Trans. On Nucl. Science, Oct. 2004, vol. 51, n. 5, 2328-2336

[26] B. Pain et al., *An enhanced performace CMOS imager with a flushed-reset Photodiode Pixel*, IEEE Trans. On Electron Devices, January 2003, vol. 50, n. 1, 48-56

[27] J. Velthuis et al., *A particle detector in 0.25 μm CMOS technology*, presented at Vertex 2004, Como, Italy, to be published on Nucl. Instruments and Methods A

[28] R.Turchetta et al., *CMOS Monolithic Active Pixel Sensors MAPS: new 'eyes' for science*, presented at Vertex 2004, Como, Italy, to be published on Nucl. Instruments and Methods A

[29] N.R.Waltham et al., *Development of a Large-Format Science-Grade Monolithic CMOS Active Pixel Sensor for Extreme Ultra Violet Spectroscopy and Imaging*, these Proceedings

[30] Albert J. P. Theuwissen, *Solid-State Imaging with Charge-Coupled Devices*, Kluwer Academic Pulishers, Norwell, 1995

[31] P. Allport et al, *CMOS Sensors for High Energy Physics*, Extended programme of the 2005 IEEE Workshop on CCD and Advanced Image Sensors

[32] N.R.Waltham, L.L.Jones, A.Fant, M.French, *A single-chip CDS and 16 bit ADC CCD Video Processing ASIC*, these proceedings